The 88” Cyclotron

Larry Phair
Nuclear Science Division
Lawrence Berkeley National Laboratory

Outline

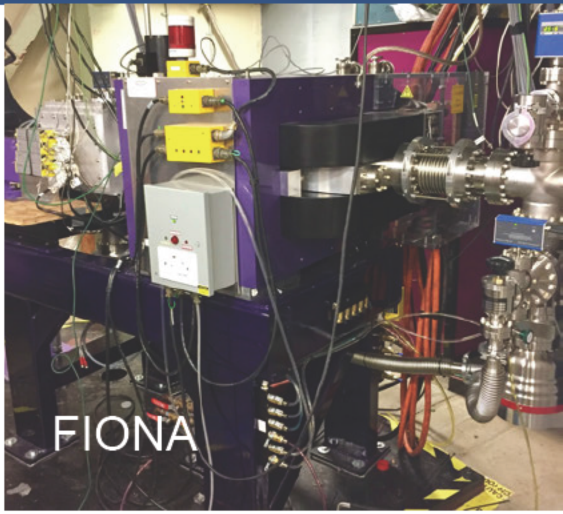
- Two missions
  - Nuclear Science program (DOE)
  - Support the nation's Nuclear Space Security (NSS) efforts
- Cyclotron specs
- Core capabilities
  - BASE Facility (cocktails)
  - Ion source development
- Cyclotron operation
- Future plans: higher energies

88-Inch Cyclotron Dual Mission

Conduct world class science

Support national security and other US space programs in the area of radiation effects testing

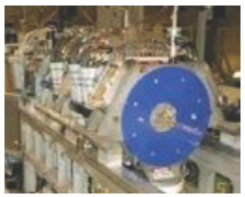
- Element 115 mass measurement: intense beams needed. 1 particle microamp of ^{48}Ca for SHE production
- Mass measurement completed (successfully!). Publication went out yesterday (PRL)



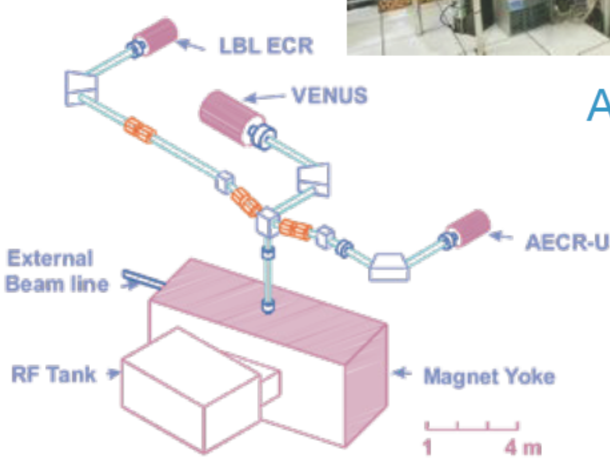
- Historically, Cyclotron funded by DOE, NRO, USAF in a 60:20:20 split
- Interagency Agreement (IA): FY2018 and beyond with USAF and NASA

88-inch accelerator

6.4 GHz ECR



VENUS: 18+28 GHz



88 - Inch Cyclotron

AECR: 10+14 GHz

High Intensity Light Ions

Protons to 60 MeV

^{3}He to 170 MeV

Heavy Ions

5 To 32 MeV/nucleon

$0.2 \leq Q/M \leq 0.5$

Mass Resolution

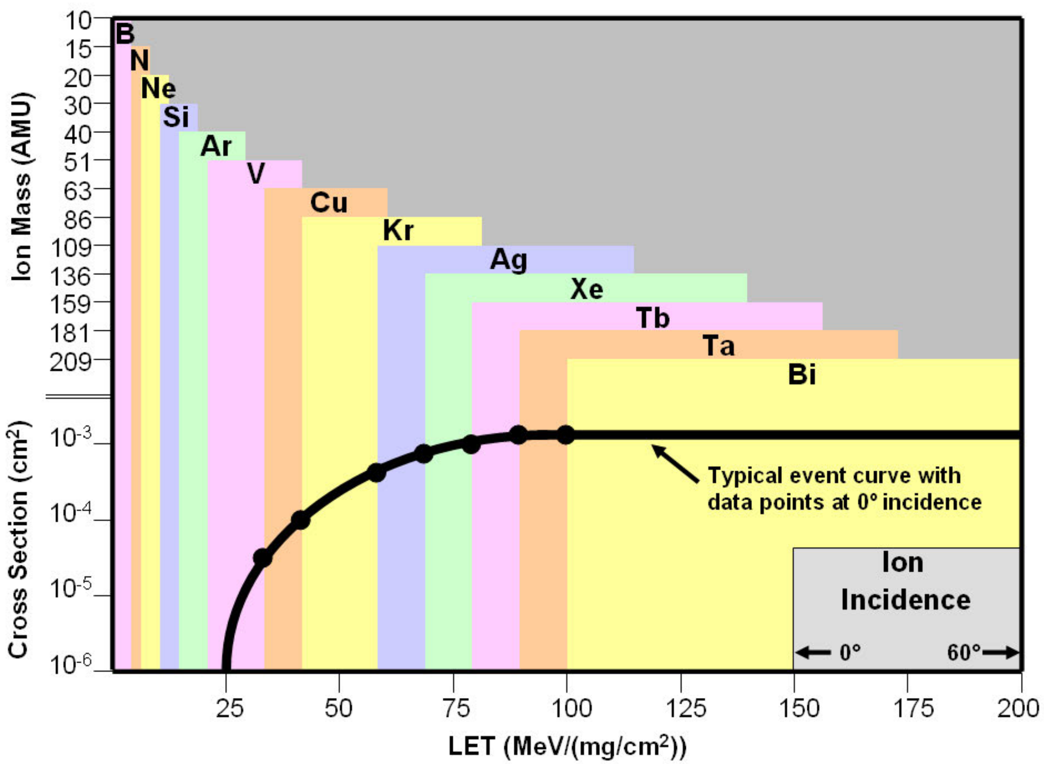
1/3000

“Beam cocktails”

$$\frac{E}{M} = \left(\frac{Q}{M}\right)^2 \times K$$

→ Medium to very high charge states of every element from H to U

BASE Cocktails



What is a 'cocktail'?

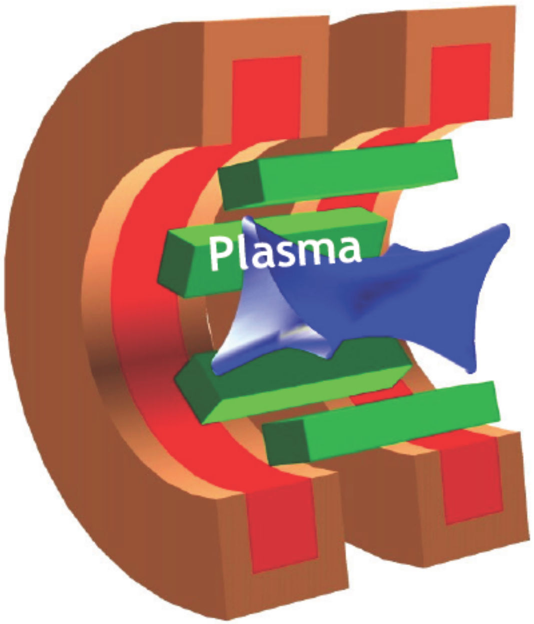
- Multiple ion species are injected into the Cyclotron simultaneously, which are then selected and separated by simply changing the frequency.
- Normally, it would take hours to retune the Cyclotron to a new ion. With our ion sources, we can change ions in less than 3 minutes.

ECR Ion Source Physics

ECR: Electron Cyclotron Resonance

$$\frac{e \cdot B_{ECR}}{m_e} = \omega_{\mu-wave}$$

$$\omega_{\mu-wave} = 28GHz \qquad B_{ECR} = 1T$$



Key Ingredients

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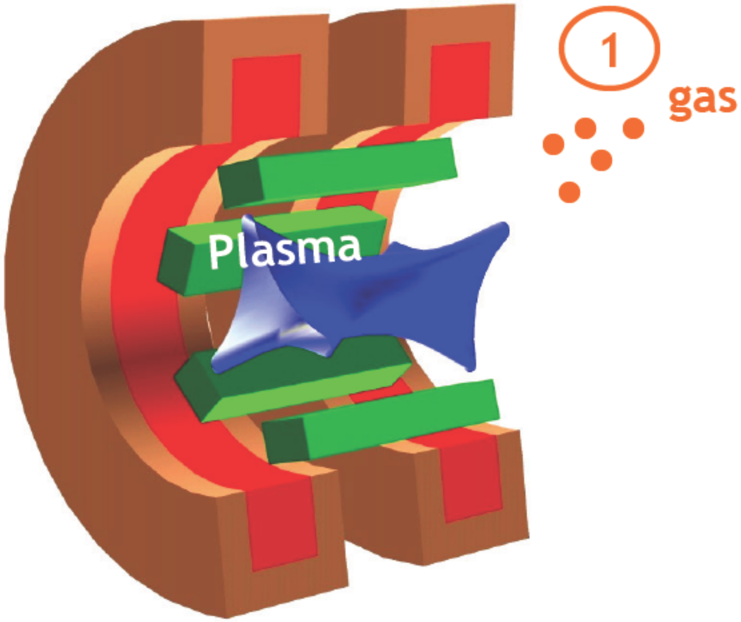

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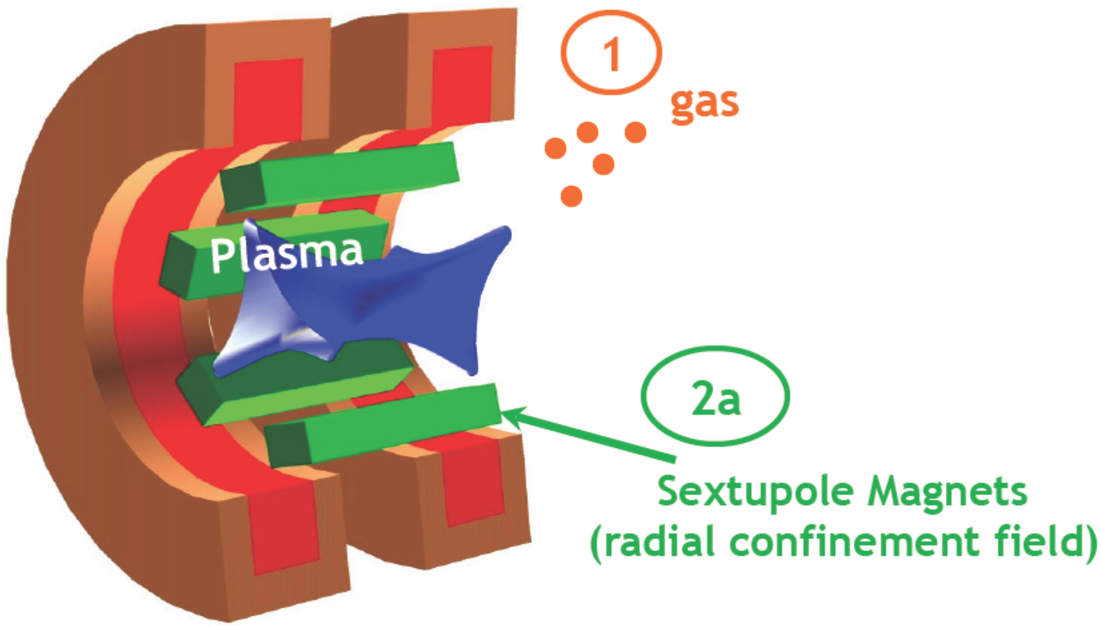

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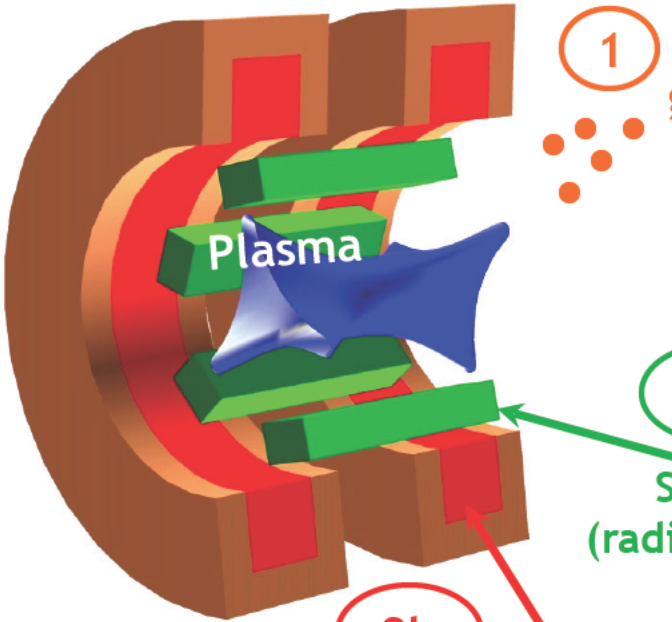

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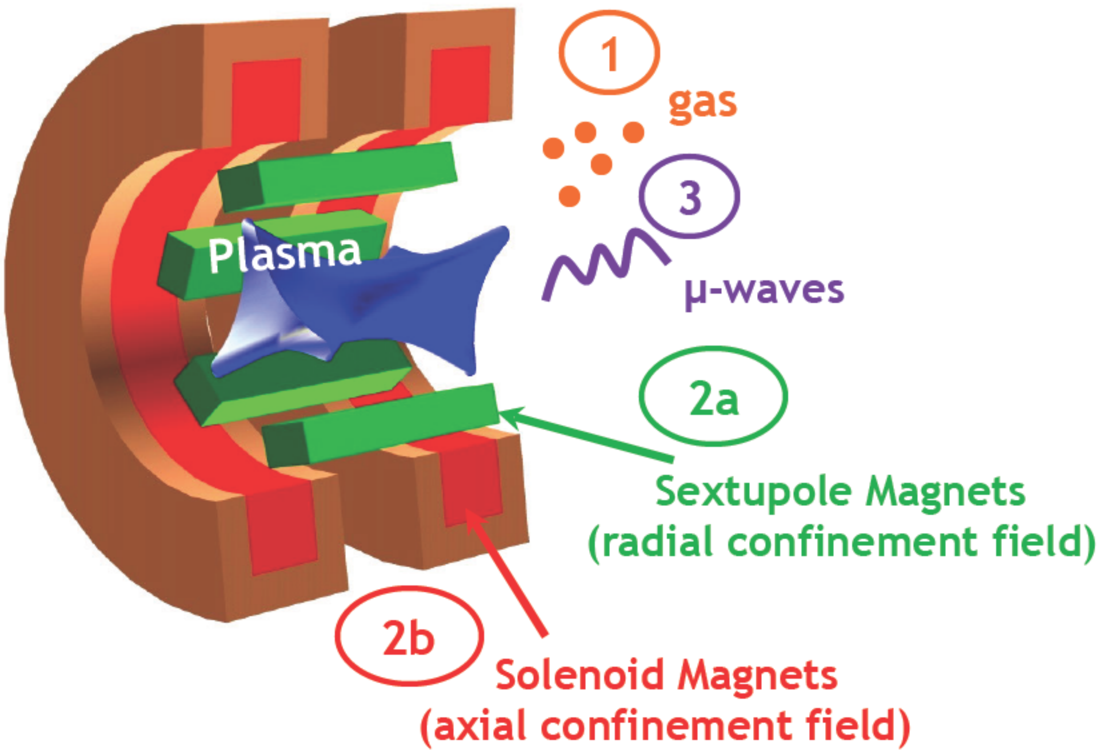

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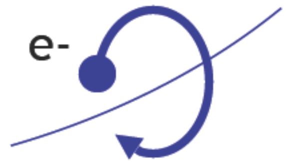

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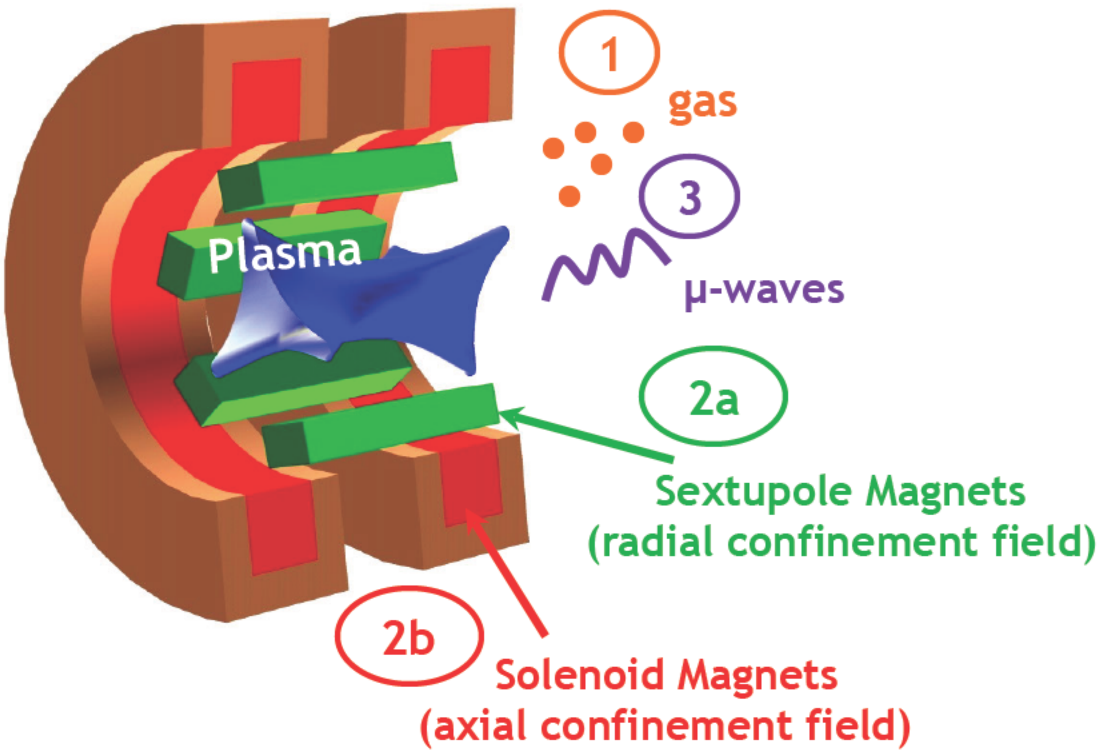

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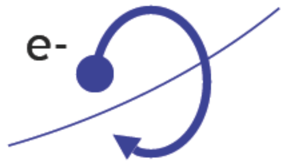

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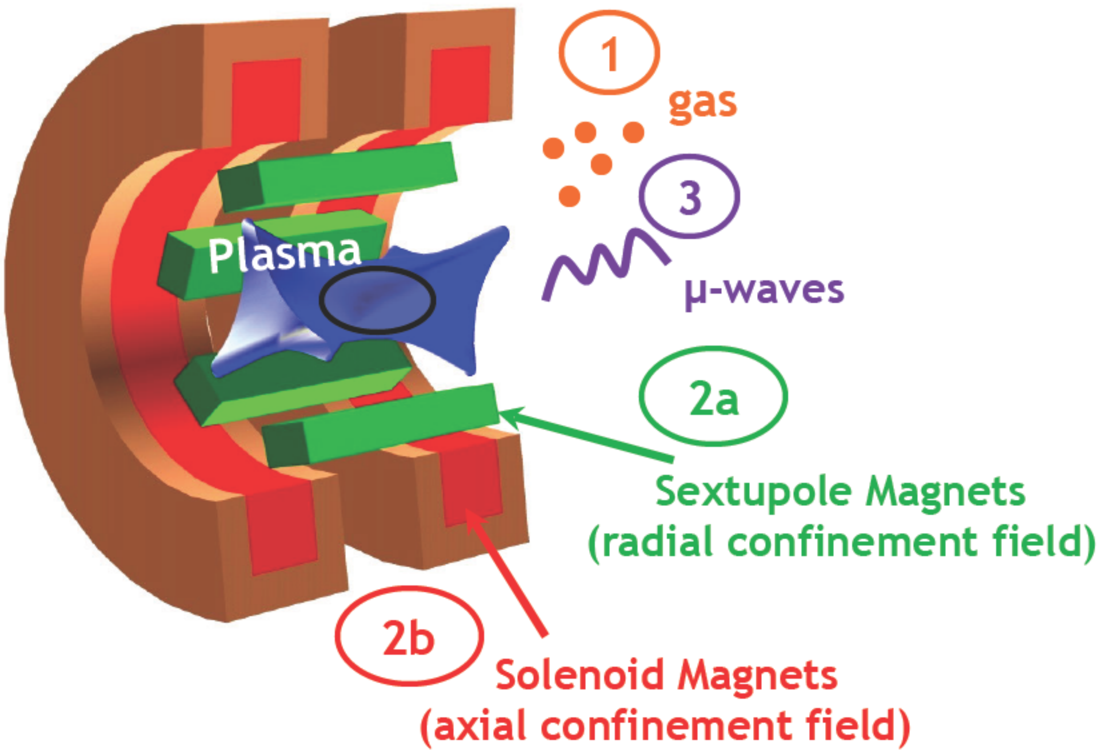

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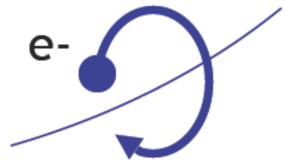

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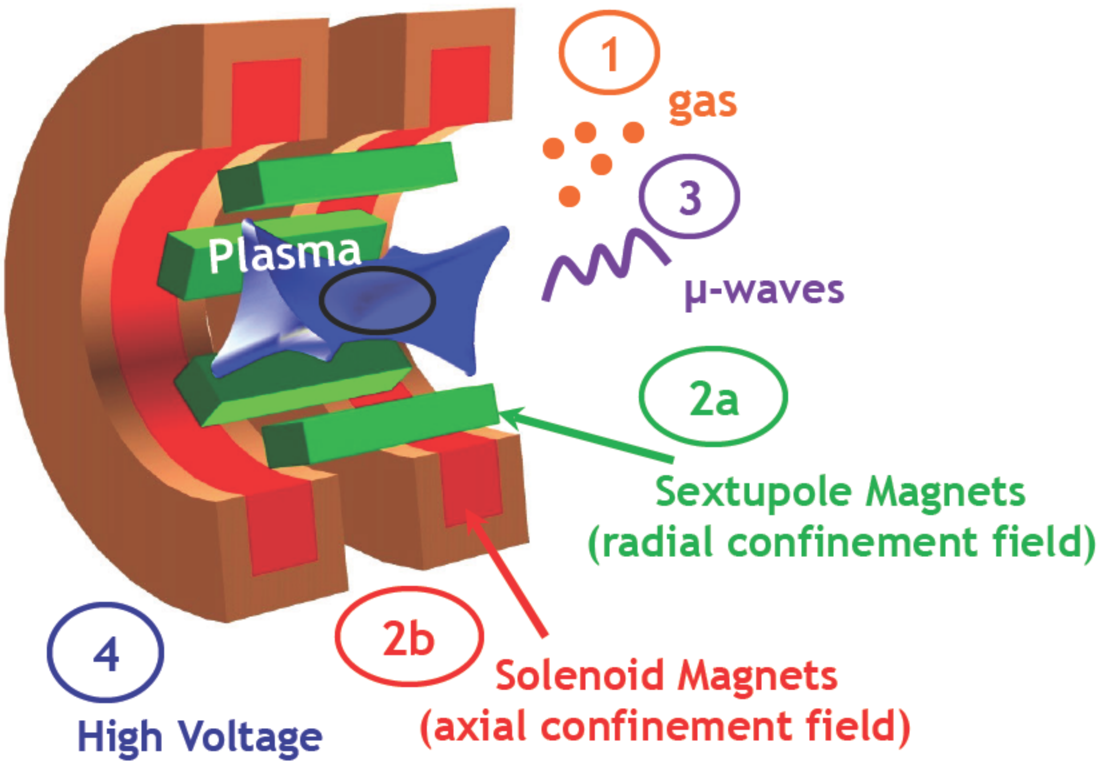

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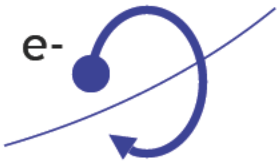

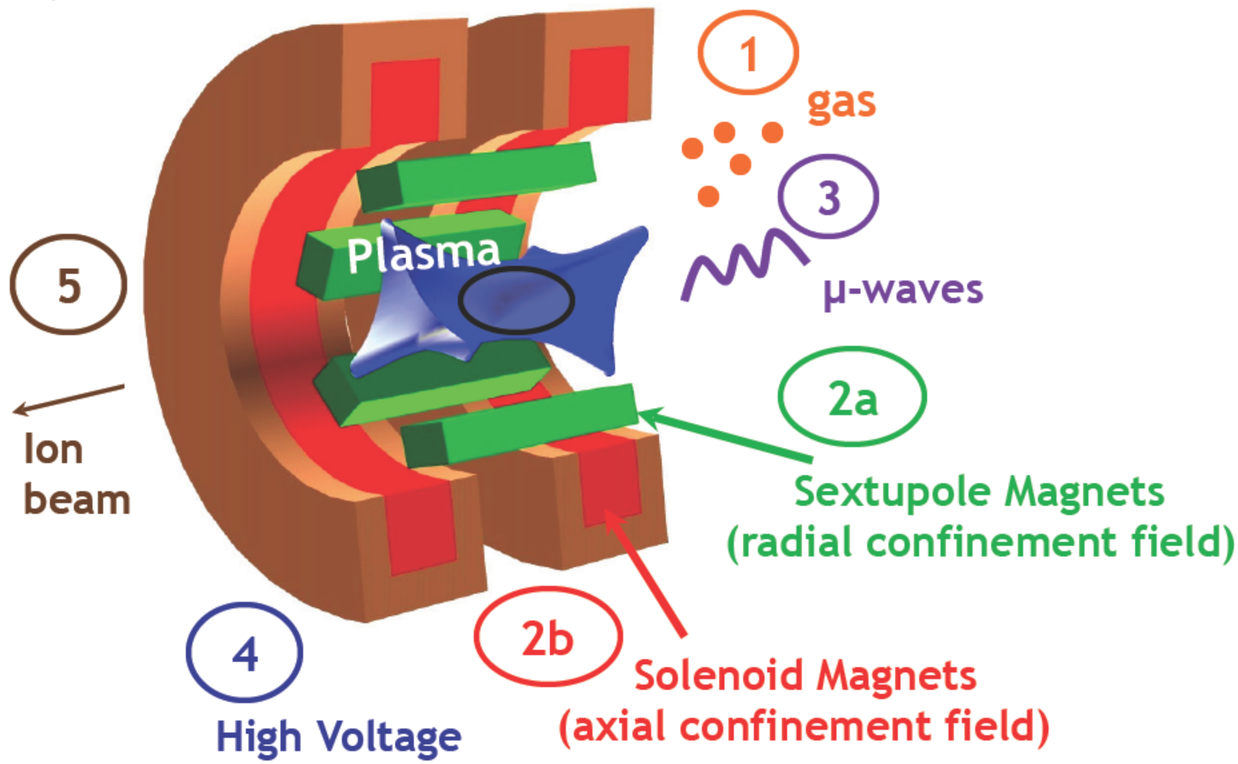

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5 Ion beam

Ion sources at the 88-Inch Cyclotron

ECR
1983

Max B-Field: 0.4T

Frequencies: 6.4GHz

Max Power: 0.6kW

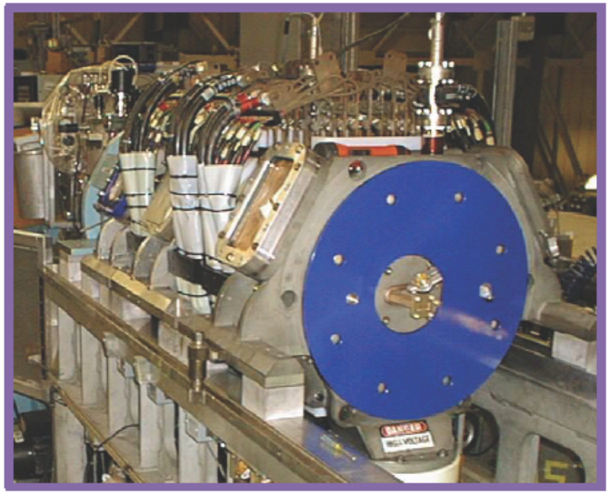
AECR-U
1996

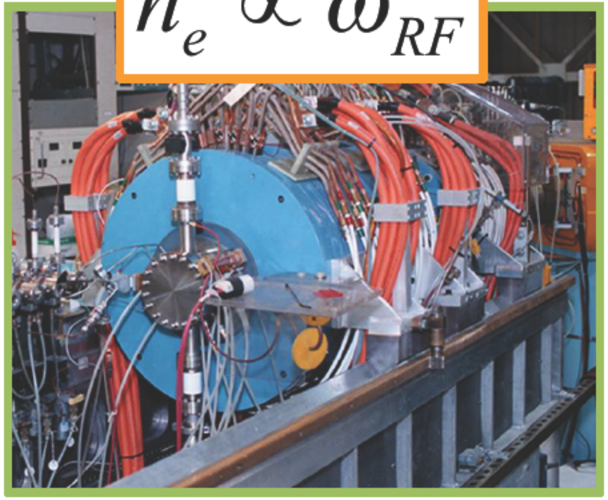
Max B-Field: 1.7T

Frequencies: 10, 14GHz

Max Power: 2.6kW

$$n_e \propto \omega_{RF}^2$$





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AECR-U
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Max B-Field: 1.7T

Frequencies: 10, 14GHz

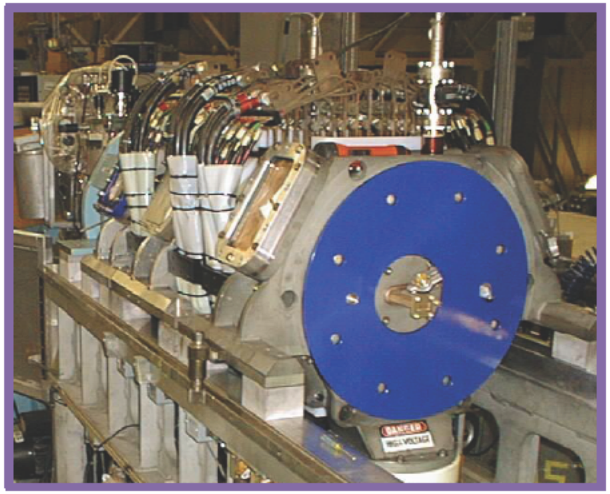
Max Power: 2.6kW

VENUS
2004, 2008 for operations

Max B-Field: 4.0T
(superconducting)
Frequencies: 18, 28GHz

Max Power: 12kW

$$n_e \propto \omega_{RF}^2$$

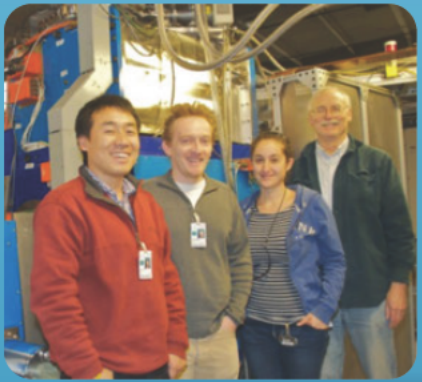


Why intense beams are important...

FRIB

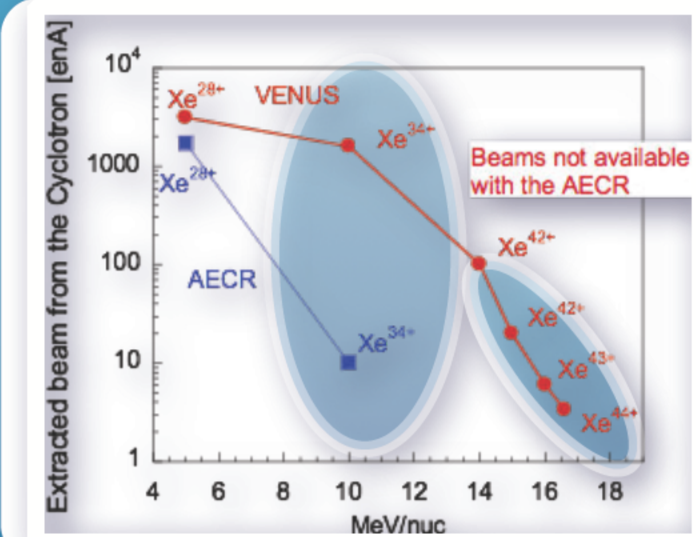
FRIB needs very high intensity high-charge-state beams.

Low emittance beams for high intensity transmission (super heavy studies)



Collaboration with MSU

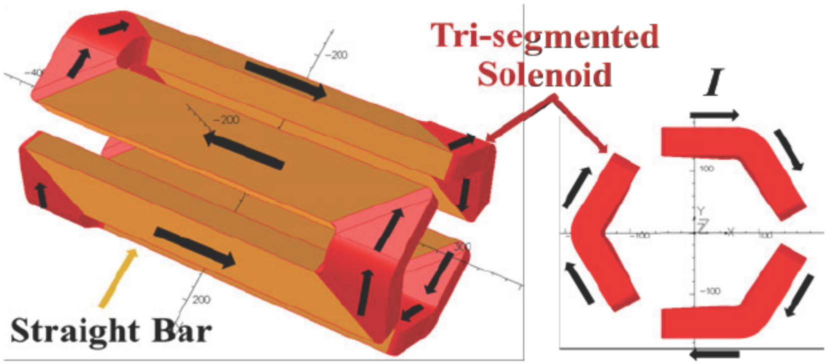
$^{238}U^{33+}$: 430 μA



- Next generation ECR ion source at “older” facilities could be a path forward for increased heavy ion use
  - UC Davis
  - TAMU

The core of MARS: a closed-loop-coil

A closed-loop hexagon coil



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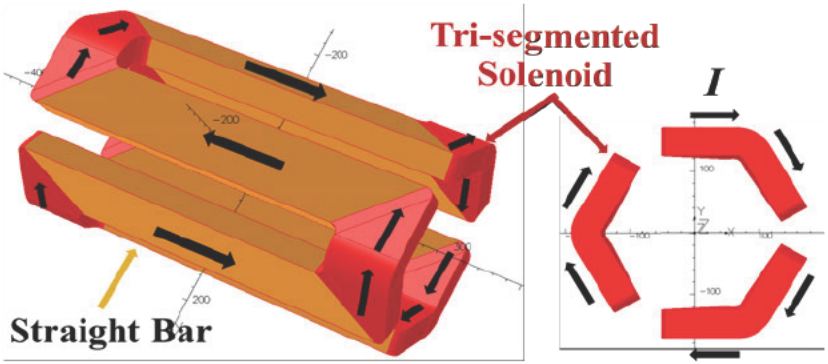

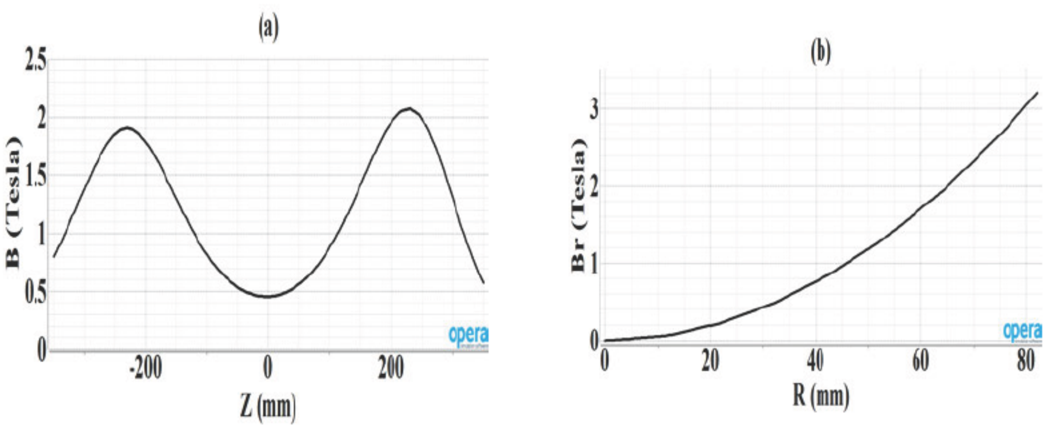

The Closed-loop Coil (ClC) generates a minimum-B configuration by itself, except the axial mirrors are not high enough for applications in ECRIS.

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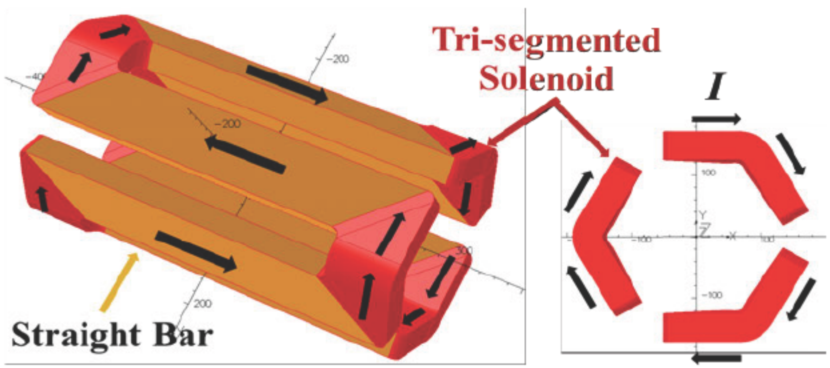
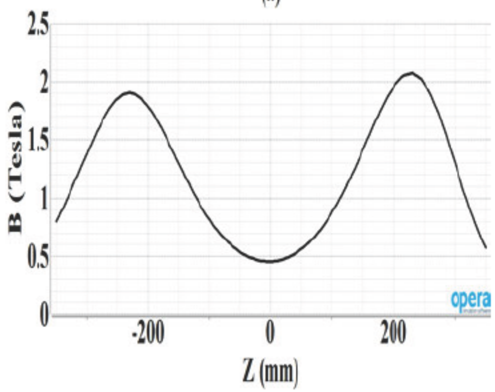


(a)



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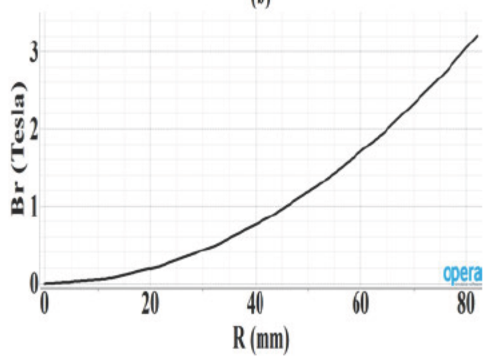

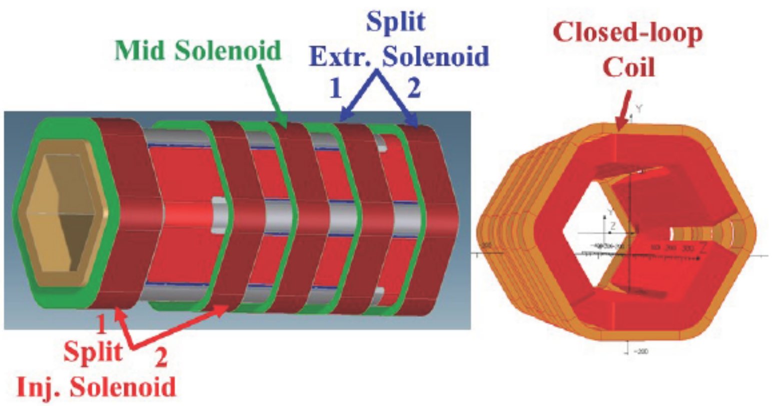

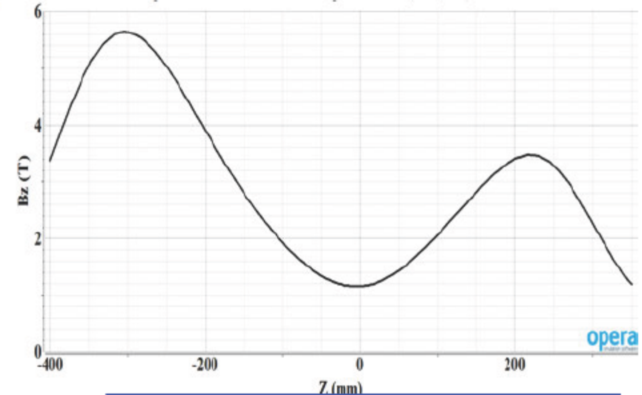

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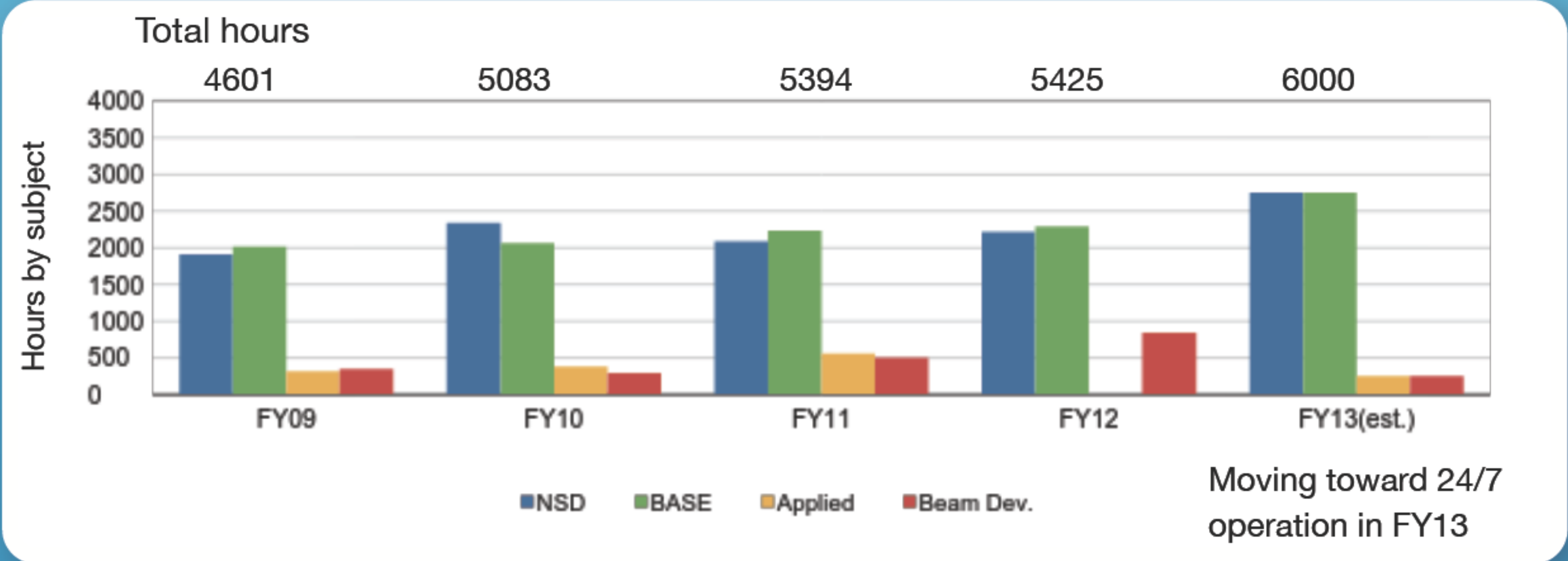
Hours run @ 88” Cyclotron

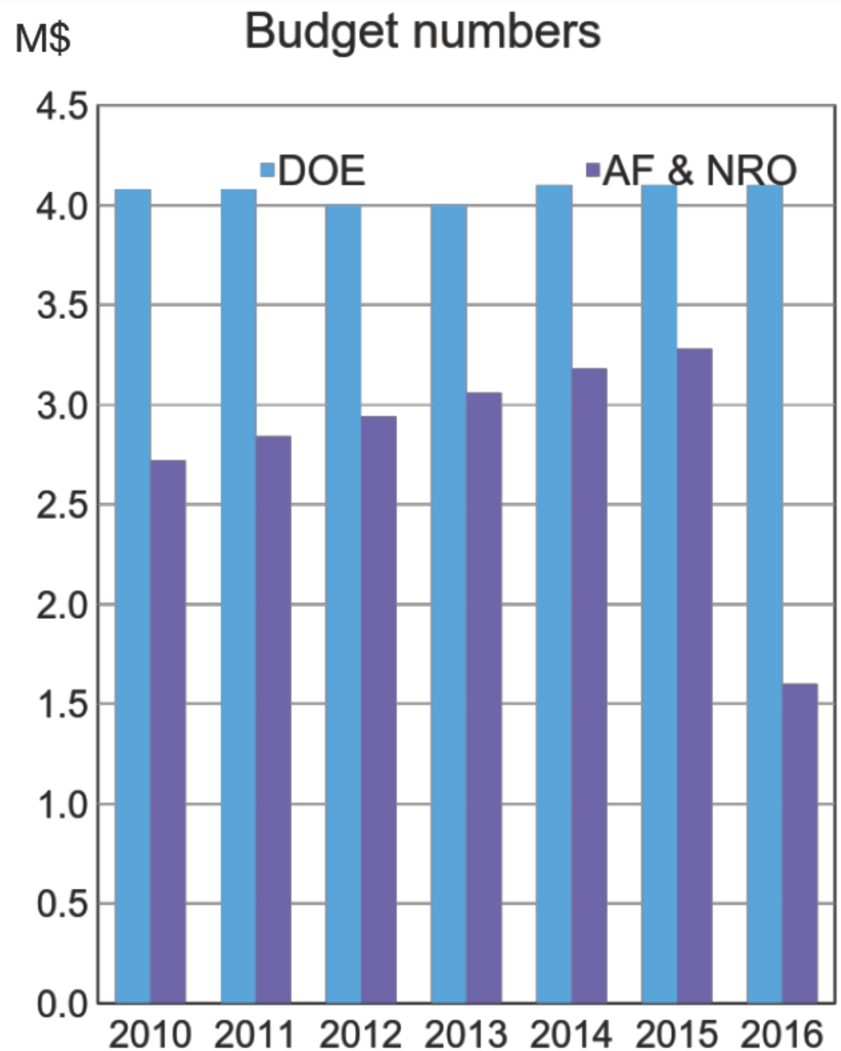


- Beam time is split roughly:
- **60%** local science program (BGS+others)
  40% chip testing (BASE Facility)

The 88-Inch Cyclotron: Thoughts and Concerns

- For more than ten years, Cyclotron had been jointly funded by DOE, NRO, USAF in a 60:20:20 split
- In FY16 and FY17, funding came from DOE and AF (only). BASE funding cut in half.
- Low funding meant reduced number of hours in FY16 and FY17. **3500 hours**
- For FY18, NASA and USAF together, $2.2M

Needed: stable funding



The future…

Linac booster: Sami Tantawi, Stanford.

The future…

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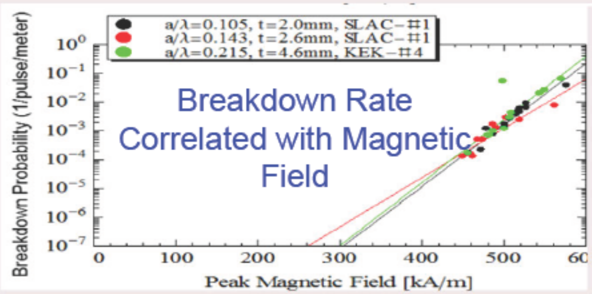
Core Areas of Research for the Advancement of RF Accelerator Technology

SLAC

Physics of Breakdown

Discovery of Magnetic Field's Role in Breakdown Triggered New Research Initiative

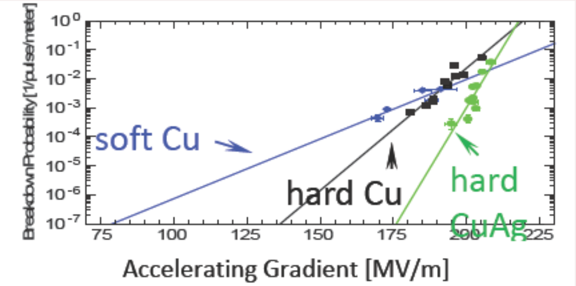
- Achieved through studies of surface electric and magnetic fields, processing techniques, surface finish



Materials Science

Investigate Materials to Improve the Performance of High Gradient Accelerating Structures

- Enhanced performance with increasing material strength
- Low temperature operation also increases the



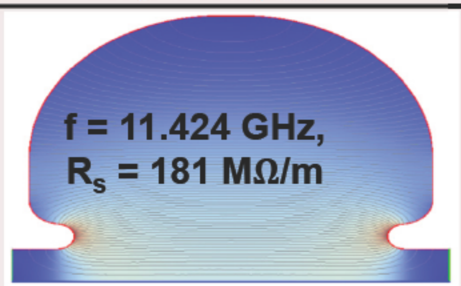
Innovative Electrodynamics

Geometry of Accelerating Structures Optimized Accounting for:

1. **_Our New Understanding of the Physics of Breakdown (magnetic fields, materials etc.)_**

   AND

2. **_The Beam Parameters Required for a Specific_**

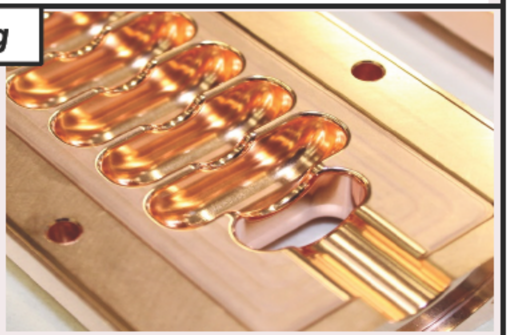


Geometry optimizations for accelerator structures based on reduction of the magnetic surface field

Manufacturing Engineering

Manufacturing Techniques that are Compatible with Superior Materials and Unique Geometries

- Low temperature assembly with clamped structures and welding
- Split-block machining for increased flexibility in fabricating advanced structures and reducing



Novel split-block assembly for novel gap accelerator

Summary- Solid Foundation for Extending to Higher Frequency and Gradient

- Gradients increased by factor of ~3, from 65 MV/m to > 170 MV/m
- *Very high shunt impedance* can improve RF to beam efficiency
- New Structure Topologies could go beyond 200 MV/m ***efficiently***:
  - ***Pave the way for future high energy colliders***
  - ***Revolutionize proton accelerators***
  - ***Provide an economical driver for plasma wakefield accelerators***
- New RF source designs improve efficiency and lower voltages:
  - Efficient modulators with short rise and fall times
  - Eliminate pulse compression for much higher system efficiency
  - Klystrons with no electromagnets and cost effective depressed collectors
- High efficiency allows NCRF operation beyond 10 KHz
- Many other applications - light sources, medical linacs, ...

Properties of 10 MeV/nucleon cocktail beam

- Beam species typically present in 10 MeV/nucleon cocktail:
  $^{11}B^{3+}$, $^{18}O^{5+}$, $^{22}Ne^{6+}$, $^{40}Ar^{11+}$, $^{65}Cu^{18+}$, $^{86}Kr^{24+}$, $^{124}Xe^{34+}$, $^{197}\underline{Au}^{52+}$

- Acceleration of different beam species requires shifting cyclotron frequency:
  - Frequency range for cocktail: 6.79 to 7.17 MHz
  - Velocity range for cocktail: β=0.145±3%

- Extract 0.03-10 enA from cyclotron (0.4-800 particles per bunch). Users often attenuate to ~10^5 particles per second, or about one particle every 70 bunches

- Cyclotron beam pulse length: ~5 ns. Using ~10^5 bunches of this length each second means the "beam there" duty factor is in the range of 0.05%

What we are looking for in a post-accelerator

We'd like a post-accelerator that can demonstrate:

- increase the energy of 10 MeV/nucleon beams to at least 25 MeV/nucleon (equivalent of 55 MV acceleration voltage)
- accept the 10 MeV/nucleon beam's velocity range (v_0 ±3%)
- accelerate ~ 10^5 particles every second roughly evenly spaced in time
- have an overall length measured in the low tens of meters

Linac booster solution that scales. Next milestones:

- De-lidding solution (as in "no"), **100 MeV/nucleon**
- Test as you fly, **250 MeV/nucleon**

White paper this summer

Summary

- The 88” Cyclotron successfully supports both a super-heavy element program and an applied program (BASE).
- Stable funding needed for successful operation
- MARS ECR ion source is at the forefront of ECR ion source development and would provide an upgrade path for the radiation effects testing community
- An energy upgrade path for the 88-Inch Cyclotron (linac booster) may be feasible.